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Some Cabibbo-Suppressed Decays of the D⁰ Meson *

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Abstract

Using data from the Fermilab photoproduction experiment E691, we have measured branching ratios for the Cabibbo-suppressed decays $D^0 \rightarrow \overline{K}^0 K^+ \pi^-$, $D^0 \rightarrow K^0 K^- \pi^+$, $D^0 \rightarrow K^- K^+ \pi^- \pi^+$, and $D^0 \rightarrow \pi^+ \pi^+ \pi^- \pi^-$. The data show evidence for several quasi-two-body decays including $D^0 \rightarrow K^{*+} K^-$ and $D^0 \rightarrow \overline{K}^{*0} K^{*0}$, but not $D^0 \rightarrow K^{*-} K^+$. The relative rates of the charged decays indicates that final state mesons containing virtual W^+ decay quarks are more likely to emerge as vector mesons than are those containing the spectator quarks. The high rate observed for $D^0 \rightarrow \overline{K}^{*0} K^{*0}$ indicates that hadronic final state interactions play a measureable role in charm decays.

Some Cabibbo-Suppressed Decays of the D^0 Meson

Introduction In an experiment using the Fermilab Tagged Photon Spectrometer (TPS), E691 has observed several Cabibbo-suppressed decays of D^0 mesons whose relative branching ratios help elucidate the processes responsible for charm decay and the evolution of the hadronic final state. Feynman diagrams for various types of Cabibbo-suppressed decays are shown in Figure 1. Spectator decays occur when $c \to d[W^+ \to u\bar{d}]$ (Figures 1a and 1b) or $c \to s[W^+ \to u\bar{s}]$ (Figures 1c and 1d). Exchange decays occur when $c \to d$ (Figure 1e) or $\bar{u} \to \bar{s}$ (Figure 1f). When the quarks produced in the weak interaction combine directly to form the final state mesons (without hadronic final state interactions), these processes produce characteristic final states. Specifically, spectator decays will not produce quasi-two-body final states where both particles are neutral and strange ($K^0\overline{K}^0$, $K^0\overline{K}^{*0}$, etc.). Exchange decays may produce such final states, but GIM cancellation will suppress the rate[1]. Only if hadronic final state interactions are important[2,1] will these neutral strange/anti-strange final states be produced at a rate comparable to that of other Cabibbo-suppressed states. Examining the spectator decays of Figure 1, only 1d may produce quasi-two-body final states with two charged, strange particles. One of these will contain the $u\bar{s}$ from the virtual W^+ and the other will contain the spectator $\bar{u}$ and the remaining s. As the decay widths for $D^0 \to K^{*+}K^-$ and $D^0 \to K^+K^{*-}$ have precisely the same phase space and form factors, their relative branching ratio is determined by the underlying dynamics (matrix element) with none of the complications found when one of the particles is strange and the other not. In this Communication we present results from the analysis of $D^0 \to K_S^0 K^- \pi^+$, $D^0 \to K_S^0 K^+ \pi^-$, $D^0 \to K^- K^+ \pi^- \pi^+$, and $D^0 \to \pi^+ \pi^+ \pi^- \pi^-$ decays which bear on these questions.

The TPS is an open geometry, two-magnet spectrometer. Photons with energy between 80 GeV and 240 GeV interacted in a 5 cm beryllium target. Silicon microstrip detectors (SMDs) and drift chambers tracked charged particles. Two threshold Čerenkov counters, divided into a total of 60 cells, provided particle identification. The nine plane SMD system separated charmed particle decay vertices from primary interaction vertices. The resolution in longitudinal vertex separation distance between primary and secondary vertices, σ_z, was typically 300 μm for a D momentum of 60 GeV and varied almost linearly with D momentum. Reconstructed charmed particles generally had momenta between 30 GeV and 120 GeV. More complete descriptions of the detector, of our particle identification and vertexing algorithms, and of related results are found in References 3 - 6.

$\underline{D^0 \rightarrow K_S^0 K^\pm \pi^\mp}$ The decays $D^0 \rightarrow K^0 K^- \pi^+$ and $D^0 \rightarrow \overline{K}^0 K^+ \pi^-$ may be produced directly with non-resonant three-body final states or with $K^* K$ quasi-two-body final states. Spectator processes followed by simple quark combination allow $K^{*+} K^-$ and $K^{*-} K^+$ final states but not $K^{*0} \overline{K}^0$ or $\overline{K}^{*0} K^0$ final states (see Figure 1d). Exchange processes followed by quark/anti-quark pair creation ($s\bar{s}$ for Figure 1e and $d\bar{d}$ or $u\bar{u}$ for Figure 1f) allow all these charge combinations. Exchange diagrams are expected to be helicity suppressed, and the diagrams which produce $(d\bar{s}, s\bar{d})$ final states interfere destructively through the GIM mechanism so that the amplitude leading to $K^{*0} \overline{K}^0$ and $\overline{K}^{*0} K^0$ final states is additionally suppressed.

We distinguish D^0 candidates from $\overline{D}^0$ candidates by looking at the charge of the bachelor pion in $D^{*+} \rightarrow D^0 \pi^+$ and charge conjugate decays. In the analysis which follows, we distinguish between $D^0 \rightarrow K_S^0 K^- \pi^+$ and $D^0 \rightarrow K_S^0 K^+ \pi^-$ but we do not distinguish between these and their charge conjugate $\overline{D}^0$ decay processes. For the study of $D^0 \rightarrow K_S^0 K \pi$ we required a well-identified $K_S^0 \rightarrow \pi^+ \pi^-$, an oppositely charged $K\pi$ pair with Čerenkov system joint probability > 0.2, and an extra (bachelor) π such that the mass difference, $\Delta M =$ mass($K_S^0 K \pi \pi$) - mass($K_S^0 K \pi$), lay in the range 0.144 GeV - 0.147 GeV, ie., consistent with the hypothesis $D^{*+} \rightarrow D^0 \pi^+$; $D^0 \rightarrow K_S^0 K \pi$. Requiring a bachelor π from D^* decay reduced backgrounds substantially and allowed identification of the D as particle or antiparticle. The $K\pi$ pair was required to form a good vertex at least 8 σ_z downstream from a primary vertex candidate, which was required to lie within 80 μm of the D^0 line of flight. At most one track other than those from the D^* was allowed to pass within 80μm of the D^0 vertex and the K and π tracks from the D^0 candidate had to pass closer to the D^0 vertex than to the primary vertex.

The $D^0 \rightarrow K_S^0 K^- \pi^+$ sample (as distinct from the $D^0 \rightarrow K_S^0 K^+ \pi^-$ sample) was divided into three exclusive sets according to consistency with the hypotheses $K^0 \overline{K}^{*0}$, $K^{*+} K^-$, and non-resonant $K^0 K^- \pi^+$. The first set consisted of all events with |mass($K^- \pi^+$)−892 MeV| < 40 MeV and $|\cos\theta| > 0.30$ where θ is the polar angle of the K^- in the $K^- \pi^+$ CM, $\theta = 0$ is the direction of the $K^- \pi^+$ system in the $K_S^0 K^- \pi^+$ CM. ($D^0 \rightarrow K^* K$ is a pseudo-scalar $\rightarrow$ vector plus pseudo-scalar decay with an angular distribution dN/dcos$\theta \propto \cos^2\theta$.) The second set consisted of the remaining events with |mass($K_S^0 \pi^+$) − 892 MeV| < 40 MeV and $|\cos\theta| > 0.30$, θ appropriately defined. The third set consisted of the remaining events. Most $K^0 \overline{K}^{*0}$, $K^{*+} K^-$, and non-resonant events should be observed in the first, second, and third sets, respectively. We generated and reconstructed Monte Carlo $K_S^0 \overline{K}^{*0}$, $K^{*+} K^-$, and non-resonant samples from which we determined the efficiency matrix ϵ_{ij} for detecting process j in set i. A maximum likelihood fit using ϵ_{ij} then determined the number of events produced via each process along with the observed background in each set. The $D^0 \rightarrow K_S^0 K^+ \pi^-$ sample was divided and fit similarly.

The histograms of the $D^0 \rightarrow K_S^0 K^- \pi^+$ data for each of the sets defined above and for the combined sample are shown in Figure 2. The curves are the projections of the

maximum likelihood fit (not independent fits of the samples shown). No signal is seen in the $K^0\overline{K}^{*0}$ sample; a clear signal is seen in the $K^{*+}K^-$ sample; some signal may exist in the non-resonant $K_S^0 K^-\pi^+$ sample. To calculate absolute branching ratios we first corrected the fitted signals for $K^0 \to K_S^0$, $K_S^0 \to \pi^+\pi^-$, and $K^* \to K\pi$ branching ratios. We then normalized to our $D^{*+} \to D^0\pi^+$; $D^0 \to K^-\pi^+$ signal corrected for its efficiency and the MARK III absolute branching ratio[7] for $D^0 \to K^-\pi^+$, $4.2 \pm 0.4 \pm 0.4\%$. These branching ratios, or 90 % confidence level upper limits, are listed in Table I, as are the results for the $D^0 \to K_S^0 K^+\pi^-$ channels. The errors on the signals of each charge mode are correlated due to the overlapping acceptance for processes leading to the same final state. Even so, we can draw a fair conclusion that $D^0 \to K^{*+}K^-$ is observed while $D^0 \to K^0\overline{K}^{*0}$ is not. We also observe no $D^0 \to K^+K^{*-}$. This asymmetry between the branching ratios to $K^{*+}K^-$ and K^+K^{*-} distinguishes $W^+ \to$ vector decays from spectator $\to$ vector decays despite their equivalent (charge conjugate) quark content. This observation therefore constrains models which describe the evolution of quark states into exclusive final states[8].

$\underline{D^0 \to K^-K^+\pi^-\pi^+}$ The decay $D^0 \to K^-K^+\pi^-\pi^+$ may be produced directly with a non-resonant four-body final state or with quasi-two-body or quasi-three-body final states in which two or more of the final hadrons are products of K^*, ρ, and/or ϕ decay. Separating $D^0 \to K^{*0}K^-\pi^+$ from $\overline{K}^{*0}K^+\pi^-$ would require restricting the sample to those D^0s from D^*s. This sample is too small for analysis by itself. Hence, we combine all $K^-K^+\pi^-\pi^+$ candidates and report the sum of the branching ratios for $D^0 \to K^{*0}K^-\pi^+$ and $D^0 \to \overline{K}^{*0}K^+\pi^-$.

We considered D^0 candidates from a D^* sample and from a non-D^* sample. In both samples we required a combined Čerenkov probability greater than 0.15 for the $KK\pi\pi$ hypothesis. The vertexing, isolation, and point-back criteria were similar to those for the $K_S^0 K\pi$ analysis, but with required vertex separation of 6 σ_z for the D^* sample and 12 σ_z for the non-D^* sample. For the non-D^* sample we additionally required all four of the D-decay tracks to pass through both magnet apertures and allowed no extra tracks within 80 μm of the secondary vertex (except those consistent with being bachelor π's from D^* decays). The $K^-K^+\pi^-\pi^+$ data were divided into four mutually exclusive sets which are shown in Figure 3. The first contains those events with $\phi \to K^+K^-$ candidates, and the remaining three contain those with two, one, or zero K^* candidates. As for the $K_S^0 K\pi$ analysis, we employed a maximum likelihood fit to extract the number of events produced with $\phi\pi^+\pi^-$, $\overline{K}^{*0}K^{*0}$, $K^*K\pi$, and non-resonant final states. As it shares the same topology, we normalized to our inclusive $D^0 \to K^-\pi^-\pi^+\pi^+$ signal and its MARK III branching ratio[7], $9.1 \pm 0.8 \pm 0.8\%$. The results are collected in Table II.

Figure 2b shows a clear signal in the $K^{*0}\overline{K}^{*0}$ sample (11 events within 20 MeV of the D^0 mass and a background of less than 1 event). The signal may include $K^*K\pi$ and non-resonant $K\pi\pi$ feed-through in addition to the $K^*\overline{K}^*$ contribution. Setting the $K^*\overline{K}^*$

contribution to zero in the maximum likelihood fit increases log likelihood by 6.8, giving a 2.6 σ $K^{*0}\overline{K}^{*0}$ signal which provides evidence for hadronic final state interactions. We also observe the $\phi\pi^+\pi^-$ final state at the 1.5 σ level. Due to our low statistics and the limited phase space available for the pions, we are unable to consider separately non-resonant $\phi\pi^+\pi^-$ and $\phi\rho$.

$\underline{D^0 \to \pi^-\pi^-\pi^+\pi^+}$ The decay $D^0 \to \pi^-\pi^-\pi^+\pi^+$ may be produced by the spectator and exchange diagrams of Figures 1a, 1b, and 1e. To study the four pion final state we required consistency with the $D^{*+} \to D^0\pi^+$ hypothesis and vertex separation and point-back criteria as for the other modes. Starting with a sample of events with evidence of a secondary vertex we demanded that 0.144 GeV $<$ ΔM $<$ 0.147 GeV, that the four pion Čerenkov system probability be greater than 0.4, that at least three of the four pions pass through both magnet apertures, that all pion momenta (four plus bachelor) be greater than 3 GeV, that the secondary vertex lie at least $8\sigma_z$ downstream of the primary vertex, and that each of the four pion tracks pass closer to the secondary vertex than to the primary vertex. The histogram of this data is shown as Figure 4. A maximum likelihood fit finds a signal of 66 ± 12 events.

To minimize differences in geometric and similar acceptances, we normalize to our signal for $D^{*+} \to D^0\pi^+$; $D^0 \to K^-\pi^+\pi^-\pi^+$, giving a ratio of branching ratios:

$$\frac{\mathrm{BR}(D^0 \to \pi^-\pi^-\pi^+\pi^+)}{\mathrm{BR}(D^0 \to K^-\pi^-\pi^+\pi^+)} = 0.096 \pm 0.018 \pm 0.007$$

for an absolute $D^0 \to \pi^-\pi^-\pi^+\pi^+$ branching ratio of $(0.87 \pm 0.16 \pm .13)\%$. Due to the combinatorial background and the similarity of the non-resonant phase space, we have not measured resonant contributions from $\rho\rho$ and $\rho\pi^+\pi^-$.

Systematic Errors The dominant uncertainties in all the direct measurements of ratios of branching ratios presented are the statistical errors due to the (relatively) large fluctuations in small samples. In addition, there are systematic errors due to the limited statistics of the Monte Carlo simulations used to determine geometric acceptance and reconstruction efficiencies, the accuracy of the Monte Carlo in simulating the data, the possible interference of non-resonant and quasi-two-body amplitudes which we are not able to determine, and the errors in the MARK III absolute branching ratios which we use in determining the absolute branching ratios given. The systematic errors due to limited Monte Carlo statistics are always much smaller than the statistical errors for the measured signals. The Monte Carlo simulation of tracking and Čerenkov simulation is generally accurate at the 5% level, and we have compared the four-body Cabibbo-suppressed modes to $D^0 \to K^-\pi^-\pi^+\pi^+$ to

minimize the systematic differences in geometric acceptance and reconstruction efficiency. The accuracy of the $K_S^0 \to \pi^+\pi^-$ reconstruction efficiency is less well known as the π tracks traverse only the drift chambers and not the SMDs. For charged tracks which traverse the SMDs, the SMDs provide great redundancy before the first magnet. However, the per track per plane efficiencies of the drift chambers, after the tracks are found, agree at the 1 - 2 % level and we believe the overall K_S^0 reconstruction efficiency is accurate $\pm 10\%$. The possible interference of non-resonant and quasi-two-body amplitudes would have a small effect on the measured rates. Altogether, we estimate that our systematic errors in the measured rates, relative to the Cabibbo-preferred modes, added in quadrature, are of order 15% . In determining the absolute branching ratios we have added MARK III's statistical and systematic errors in quadrature and then added this in quadrature with our own systematic error to give a 21% systematic error to the absolute branching ratio measurements.

Physics Summary We can compare the measurements of branching ratios presented here with the related measurements which are listed in Table III. Our inclusive branching ratios for $D^0 \to K^0 K^- \pi^+$ and $D^0 \to \overline{K}^0 K^+ \pi^-$ add (within errors) to the level reported by ARGUS[9], who did not separate these states. We see, in addition, a substantial quasi-two-body contribution from $K^{*+}K^-$, but no evidence of $K^{*-}K^+$, $\overline{K}^{*0}K^0$, or $K^{*0}\overline{K}^0$ contributions. The $K^{*+}K^-$ branching ratio, as measured, is also somewhat higher than the average K^-K^+ branching ratio. These observations are consistent with a picture where the $K_S^0 K \pi$ final state is produced predominantly from spectator decay followed by quark combination, the $u\bar{s}$ from the virtual W^+ emerging as a vector meson more often than does the $\bar{u}s$ containing the spectator $\bar{u}$. The lack of $K^{*0}\overline{K}^0$ and $\overline{K}^{*0}K^0$ indicates that decays involving W-exchange and/or final state interactions are less important than simple spectator decays.

We observe $D^0 \to K^-K^+\pi^-\pi^+$ with approximately the same branching ratio as reported by ACCMOR[10]. If we observe a $D^0 \to \phi\pi^+\pi^-$ component, it is 2 σ smaller than the ACCMOR result. We do observe a large $K^{*0}\overline{K}^{*0}$ branching ratio; the likelihood that statistical fluctuations and $K^*K\pi$ and non-resonant $K^-K^+\pi^-\pi^+$ feed-through produce such a large signal is less than 1%. The branching ratio we measure for this mode is greater than those reported by E400[11] and CLEO[12] for the similar mode $D^0 \to K^0\overline{K}^0$, but less than the $D^0 \to K^-K^+$ branching ratio[9,10,12,13]. As W-exchange amplitudes are generally found to be small, and GIM cancellation should further suppress the W-exchange amplitudes for these final states, the observations of $D^0 \to K^0\overline{K}^0$ and $D^0 \to K^{*0}\overline{K}^{*0}$ are evidence for final state interactions at levels of the magnitude predicted by Donoghue[2] and Pham[1].

Finally, we observe $D^0 \to \pi^-\pi^+\pi^-\pi^+$ (no strange particles) with a branching ratio more than twice that of $D^0 \to K^-K^+\pi^-\pi^+$ (two strange particles) where $D^0 \to \pi^-\pi^+$ (no strange particles) has a branching ratio less than half that of $D^0 \to K^-K^+$ (two strange particles). It appears that Cabibbo-suppressed decays occur more or less equally with and without strangeness at the quark final state level, although the hadronic two-body and four-body

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final states do not separately display this symmetry. This quark level symmetry is expected if simple spectator decays are dominant.

Notes and References

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Figure Captions

1. Feynman diagrams for Cabibbo-suppressed decays of mesons containing charm quarks. The dots mark the Cabibbo-suppressed vertices.

2. The observed invariant mass distributions for the (a) $\overline{K}^{*0}K^0$, (b) $K^{*+}K^-$, (c) non-resonant $K^0K^-\pi^+$, and (d) inclusive $K^0K^-\pi^+$ samples described in the text.

3. The observed invariant mass distributions for the (a) $\phi\pi^+\pi^-$, (b) $K^{*0}\overline{K}^{*0}$, (c) $K^*K\pi$, and (d) non-resonant $K^-K^+\pi^-\pi^+$ samples described in the text.

4. The invariant mass distribution for the $\pi^-\pi^-\pi^+\pi^+$ sample described in the text.

Table Captions

I The ratio of branching ratios and absolute branching ratios, or 90% confidence level upper limits, for the $K^0K\pi$ channels studied.

II The ratio of branching ratios and absolute branching ratios, or 90% confidence level upper limits, for the $K^-K^+\pi^-\pi^+$ channels studied.

III Absolute D^0 branching ratios in percent from other experiments, with the corresponding E691 results for comparison.

Decay Mode f	$\dfrac{\mathrm{BR}(D^0 \to f) \times 100}{\mathrm{BR}(D^0 \to K^-\pi^+)}$	Absolute Branching Ratio (%)
inclusive $K^0 K^- \pi^+$	$.16^{+.06}_{-.06}$	$.69^{+.27}_{-.23} \pm .14$
$\overline{K}^{*0} K^0$	$.00^{+.03}_{-.00}$	$< .13$
$K^{*+} K^-$	$.16^{+.08}_{-.06}$	$.69^{+.32}_{-.26} \pm .15$
non-resonant $K^0 K^- \pi^+$	$.06^{+.06}_{-.06}$	$< .53$
inclusive $\overline{K}^0 K^+ \pi^-$	$.10^{+.05}_{-.05}$	$.42^{+.23}_{-.20} \pm .09$
$K^{*0} \overline{K}^0$	$.00^{+.04}_{-.00}$	$< .22$
$K^+ K^{*-}$	$.00^{+.03}_{-.00}$	$< .17$
non-resonant $\overline{K}^0 K^+ \pi^-$	$.10^{+.06}_{-.05}$	$.42^{+.23}_{-.20} \pm .09$

Table I

Decay Mode f	$\dfrac{\mathrm{BR}(D^0 \to f) \times 100}{\mathrm{BR}(D^0 \to K^-\pi^+\pi^-\pi^+)}$	Absolute Branching Ratio (%)
inclusive $K^- K^+ \pi^- \pi^+$	$2.8^{+0.8}_{-0.7}$	$.26^{+.07}_{-.06} \pm .05$
$\phi \pi^+ \pi^-$	$.76^{+.66}_{-.49}$	$< .15$
$K^{*0} \overline{K}^{*0}$	$3.6^{+2.0}_{-1.6}$	$.33^{+.18}_{-.15} \pm .07$
$K^{*0} K^- \pi^+ + \overline{K}^{*0} K^+ \pi^-$	$1.0^{+1.6}_{-1.0}$	$< .28$
non-resonant $K^- K^+ \pi^- \pi^+$	$0.1^{+1.1}_{-0.1}$	$< .14$

Table II

Decay Mode	ARGUS[9]	CLEO[12]	MARK III[13]	ACCMOR[10]	E400[11]	E691[14]
$K^- K^+$	$.42 \pm .08 \pm .06$	$.46 \pm .03 \pm .05$	$.51 \pm .08 \pm .07$	$.49^{+.15}_{-.14}$		
$\pi^- \pi^+$	$.17 \pm .03 \pm .03$	$.19 \pm .03 \pm .03$	$.14 \pm .04 \pm .03$			
$\bar{K}^0 \bar{K}^0$		$.13^{+.07+.02}_{-.05-.02}$			$.10 \pm .08$	$< .13$
$\bar{K}^0 K^+ \pi^- + K^0 K^- \pi^+$	$1.00 \pm .19 \pm .38$					$1.13^{+.35}_{-.32} \pm .24$
$K^{*+} K^- + K^+ K^{*-}$	$.62 \pm .25 \pm .26$					$.66^{+.36}_{-.30} \pm .14$
$[K^- K^+]_{nr}\, \pi^- \pi^+$			0.8 ± 0.5	$.17 \pm .06$		$.27^{+.07}_{-.06} \pm .05$
$\phi \pi^+ \pi^-$				$.30 \pm .10$		$< .15$
$\pi^- \pi^+ \pi^- \pi^+$			$1.5 \pm 0.6 \pm 0.2$	$.25 \pm .10$		$.87 \pm .16 \pm .13$

Table III